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LIMITATIONS OF A TRIPLE-SENSOR PROBE IN MEASURING A HIGHLY TURBULENT WAKE FLOWFIELD

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ABSTRACT

A triple-sensor thermal anemometry probe is used to measure the highly turbulent flowfield of a wake from a stalled NACA0012 airfoil. The data analysis procedure and determination of the 'uniqueness domain' follow the method of Lekakis et al. (1989). It is found that in the high turbulence regions, the instantaneous velocity vector frequently cannot be resolved from the measured voltages. This results in a discontinuous time trace of velocity and a lower value of the time averaged turbulent statistics. Velocity spectra obtained using the triple-sensor probe and a single sensor probe show considerable differences in the higher frequencies, indicating the inability of the former to resolve eddies which are smaller than the probe tip diameter.

NOMENCLATURE

$\mathbf{U}$	= velocity vector
U_{fs}	= Free stream velocity
c	= Airfoil chord
u, v, w	= Instantaneous axial, transverse and spanwise component of velocity.
$\bar{u}, \bar{v}, \bar{w}$	= Time averaged velocity components
u',v',w'	= Root-mean-square velocity fluctuations
$\overline{u'v'}, \overline{u'w'}, \overline{v'w'}$	= Turbulent shear stresses
x, y, z	= The coordinate axes
α	= Airfoil angle of attack
β, γ	= Polar and azimuthal flow angles (see Figure 1)
δ_i, θ_i (i=1,2,3)	= Wire angles (see Figure 1)
$Q_1, h_1, T_3, D_5, G_{71}, D_8, B, G_{42}, G_{43}, L_{28}, L_{18}, L_{23}, L_{27}$	= See Lekakis et al. (1989)

INTRODUCTION

A triple-sensor probe is a natural extension of single and double-sensor probes. The use of the latter two in primarily 1 and 2-dimensional flow situations is well established. Even in such flow situations measurements of turbulence fluctuations by single and double-sensor probes are subjected to the assumption of low fluctuation intensity. A triple-sensor probe, which can resolve all three velocity components simultaneously, is highly desirable for measurements in 3-dimensional and highly turbulent flowfields.

Increasing the number of sensor elements from two to three substantially increases the complexity of the measurement process. The non-linear nature of the directional response equation implies that for certain flow angles, the three cooling velocities from the triple sensor probe may not produce any real solution of the velocity vector at all (existence problem). Moreover, as pointed out by Willmarth (1985), a measured set of three cooling velocities, using a triple-sensor probe, can be produced by as many as eight different velocity vectors, only one of which is the correct one (uniqueness problem). In the past, many investigators using triple sensor probes presumed uniqueness and existence of the solution (Lakshminarayana and Davino, 1988; Frota and Moffat, 1983). An extensive analytical study of the orthogonal triple-sensor probe using the non-linear directional response equation of Jorgensen (1971), has been developed by Chang et al. (1983) and is extended to a non-orthogonal, symmetric, tetrahedron probe by Lekakis et al. (1989)[1]. The solution procedure, an outline of which will be discussed later, determines all possible velocity vectors that can produce the measured cooling velocities, and if real solutions are obtained, singles out the right vector. The solution procedure, when used with a digital computer, produces a velocity time trace which not only enables one to determine the long time averaged statistical quantities but also to obtain unsteady information, such as velocity spectra and phase averaged quantities. Lekakis et al. showed a limited triple-sensor probe measurement of various turbulent stresses in a fully developed, turbulent pipe flow. However, the maximum turbulence fluctuations encountered in such a flowfield is not very high.

The objective of the present experiments is to use a triple-sensor probe in a highly turbulent flowfield of a wake behind a stalled airfoil, to assess various advantages and shortcomings of this probe. The data analysis procedure to obtain instantaneous velocity vectors follows the method proposed by Lekakis et al. (1989). Long time averaged mean and turbulent stresses are calculated for the above flowfield. Various difficulties faced due to limitations on the measurable flow angularity and large probe dimensions are discussed. In the following, a brief description of the probe and the uniqueness of solutions are described first, followed by a presentation of the experimental results.

PROBE GEOMETRY AND THE COORDINATE SYSTEM

The geometry of the TSI triple-sensor probe is defined in Figures 1(a) and 1(b). The orientation of each wire is described by two angles θ_i and δ_i ($i=1,2,3$). The former are the angles between the wires and a plane normal to the probe axis and δ_i are the angles formed by the projection of the wires on this plane. For the present probe δ_1, δ_2 and δ_3 are nearly 60° and θ_1, θ_2 and θ_3 are 34.9°, 35.2° and 34.9°, respectively. The sensors are mounted such that the needle interference and thermal wake interference of the sensors are minimized. The coordinate system used to define the instantaneous velocity vector is attached to the probe with the x-axis parallel to the probe axis. The polar and azimuthal angles β and γ are also defined in Figure 1(c). The velocity components in terms of β and γ are

$$\begin{aligned} u &= |U|\cos\gamma \\ v &= |U|\sin\gamma\cos\beta \\ w &= |U|\sin\gamma\sin\beta \end{aligned}$$

The solution procedure described by Lekakis et al. (1989) at first determines β by solving a 4th order polynomial equation involving $\tan\beta$. Then the angle γ and the velocity magnitude U are determined.

Uniqueness Domain

As mentioned earlier, a triple sensor probe is not versatile enough to measure any velocity vector. The solution procedure provides a real solution only if the flow velocity vector to be measured is within a restricted domain of angles with respect to the probe axis. This domain depends on the probe construction and is calculated a priori from the sensor angles (Lekakis et al. 1989). A velocity vector that falls within this domain produces eight different real solutions, out of which only one is the right solution. It is relatively easy to determine the latter for a symmetric tetrahedron probe since the other seven fall outside the predetermined domain of angles for which real solutions can exist. This restricted domain of β and γ angles for which the true velocity vector can be found is known as the 'uniqueness domain'. In Figure 2, the region enclosed by the data points around $\gamma = 0°$ is the 'uniqueness domain' calculated for the present probe geometry. This domain is symmetrical for the remaining region not shown in Figure 2. The probe cannot measure reverse flow (negative γ angles) and the maximum γ angle that can be measured is also dependent on the β angle of the velocity vector. The maxima occur when the velocity vector is nearly parallel to the sensor, i.e., $\beta \sim -30°$, 90° and -150°.

[1]A few errors have been found during a detailed derivation of the equations mentioned in this reference. The corrections are underlined.

eqn. 1: $Q_1^2 = ... + h_1^2(v\cos\delta_2 - w\,\underline{\mathrm{Sin}\delta_2})^2$

eqn. 14(c): $T_3 = 2(D_5\sin\beta \underline{\pm} G_{71}\cos\beta)$

after eqn. 19(b): $D_8 = 0 \rightarrow B = G_{42}/\underline{G_{43}}$

Appendix: $L_{28} = L_{18} \underline{\pm} L_{23} + L_{27}$

EXPERIMENTAL PROCEDURE AND RESULTS

The triple-sensor probe is used to measure the time mean velocity components and various Reynolds stresses in the wake of an NACA0012 airfoil mounted in a low speed wind tunnel. The details of the wind tunnel can be found in the reference Zaman et al. (1989). The free stream turbulence intensity in the tunnel is very low, less than 0.1%. The airfoil has a chord of 10.2cm and an aspect ratio of 7.5. The chord Reynolds number for all data presented here is about 60,000. Each sensor of the 3-sensor probe was calibrated in situ using the angles provided by TSI Inc. Three TSI 1050 constant temperature anemometers are used with the triple-sensor probe. The analog signals from the anemometers are digitized using a dsp Technology sample and hold digitizer unit and then stored and analyzed by a Microvax 3300 computer. Each set of three instantaneous voltages from the triple sensor probe are analyzed to obtain the instantaneous velocity vector. Sets of voltages which cannot be resolved are neglected for data processing.

Time Mean Measurements

Figures 3(a), (b) and (c) show the time-mean velocity and various Reynolds stress profiles measured 2½ chords downstream from the airfoil trailing edge. For these data the airfoil was mounted at $\alpha = 22.5°$ and the wake structure was dominated by periodic, large amplitude bluff body shedding vortices (Zaman et al., 1989). Passage of these vortices cause large transverse velocity fluctuations. Consequently, the rms value of the transverse velocity fluctuations (v') and the $\overline{u'v'}$ shear stress are very high. The same flowfield was measured earlier using a cross wire probe (Fig. 15, Zaman et al., 1989). The present data are qualitatively in good agreement with these measurements; although, the maximum values of the u' and v' fluctuations are somewhat smaller in the present case.

At every measurement station a set of 4096 data points containing instantaneous voltages from all 3 sensors are acquired and processed to obtain the instantaneous velocity components. However, a certain percentage of these data cannot be resolved. Figure 3(d) shows the percentage of unresolved data encountered at different y-stations. The number increases with an increase of the level of turbulence fluctuations and is maximum around the center of the wake where the turbulence fluctuations are also maximum.

To further study the unresolved data points, the measured, instantaneous transverse velocity component at the center of the wake is plotted as a function of time in Figure 4. Corresponding instantaneous voltages from one of the sensors are also shown in this figure. In both cases the data points are joined by straight lines. The time trace of velocity becomes discontinuous whenever a set of instantaneous voltages from the triple sensor probe cannot be resolved to obtain the instantaneous velocity components. Such situations appear whenever the instantaneous velocity vector moves outside the 'uniqueness domain' of the triple-sensor probe. The measured time averaged flow angle in the wake is low (within ± 5°) and at the center of the wake, for which the instantaneous v-component is shown in Figure 4, the time averaged flow angle is zero. However, Figure 4 show large swings from positive to negative values of the v-velocity component. The maximum variation in each direction is nearly equal to the local axial velocity, indicating large variation in the flow angle as well. These variations are caused by the passage of the periodic, large scale, bluff body shedding vortices. When a triple-sensor probe with a limited angular response is used in such a flowfield, frequently the velocity vector cannot be determined. One important disadvantage of such a situation is a lower value of the measured turbulent stresses, since, the largest velocity fluctuations cannot be resolved. A large number of data dropout also implies that a triple-sensor probe cannot be used to obtain phase averaged or ensemble averaged information using conventional techniques.

Velocity spectra

In order to determine the ability of a triple-sensor probe to resolve high frequency fluctuations, spectral measurements of the u-velocity fluctuations were made using both the triple and a single-sensor probe (Figure 5). For clarity, the spectrum obtained by the triple-sensor probe is shifted by one major division in Figure 5. The measurements were made 4 chords downstream of the airfoil trailing edge and the airfoil angle of attack was reduced to 2°. At this condition, the velocity fluctuations in the measurement station were low ($u'/U_{fs} = .03$ at the center of the wake) and all voltage signals from the triple-sensor probe could be resolved. The agreement between the two spectra is good in the lower frequency range up to about 500 Hz., above which, a considerable difference is clearly visible. While the spectrum from the single sensor probe shows the -5/3 decay characteristic of the inertial subrange, the spectrum from the triple-sensor is similar to that of white noise. The inability of the triple-sensor probe to resolve the high frequency fluctuations is attributed to the large probe diameter. The diameter of the circle containing all three sensors for the triple-sensor probe used in this experiment is 2mm. The frequency associated with the eddies of length scale equal to 2mm and a velocity scale equal to the wake velocity defect, $U_{fs}-\bar{u}/U_{fs}$ (= .05 at y/c = 0), is estimated to be about 230 Hz (Tennekes and Lumley, 1972). This number is of the same order of magnitude as the frequency for which the spectra from single and triple sensor probes differ. Another supporting evidence (not shown here) is the spectrum of the unprocessed voltage signal from any one of the sensors of the triple-sensor probe. Such a spectrum is very similar to that of the single-sensor probe even at the high frequency end. This shows that the smaller eddies affect the response of the individual sensors of the triple-sensor probe. However, such high frequency eddies with length scales smaller than the probe tip dimension cannot affect all three sensors effectively. Therefore, when responses from all three sensors are processed to obtain the velocity vector, information about the eddies smaller than the probe tip dimension are lost.

CONCLUSIONS

A triple-sensor probe can measure a velocity vector only if it is within a certain angle with respect to the probe reference direction. For the probe used in the present experiment, this 'uniqueness domain' was restricted mostly within a cone of 40° about the axial direction. Although the time mean velocity vector in the wake was well within this 'uniqueness domain', the instantaneous fluctuations frequently overshoot this region. The bluff body shedding vortices present in this flowfield made the velocity distribution more skewed and the probability of the instantaneous velocity vector travelling outside the 'uniqueness domain' was increased. Therefore, at the center of the wake as much as 20% of all data points could not be resolved, which resulted in a discontinuous time trace of the velocity components. The principle usefulness of a triple-sensor probe lies in its ability to measure simultaneously the u, v, w components and the Reynolds stress tensors. However, in a highly turbulent flowfield the measured stresses can be lower than the true values, since the larger fluctuations causing the velocity vector to move out of the 'uniqueness domain' cannot be measured. Moreover, a large probe volume, to accommodate the individual hot-wires, affects the ability of this probe to resolve the high frequency fluctuations.

A 2-sensor hot-wire probe also has a limited 'angle of acceptance', i,e, the velocity vector has to be within a certain angle (usually within ±35°) with respect to the probe reference direction to be resolved accurately. If the instantaneous velocity vector goes outside this 'angle of acceptance', the data analysis procedure still gives an *estimation* of the velocity vector (which can be incorrect). If a triple-sensor probe is used in such a situation, even an estimate is not available. This poses a serious problem in using a triple-sensor probe in a highly turbulent flowfield. A triple-sensor probe can be as versatile as a 2-sensor one only if a technique is developed to approximately estimate the velocity vector when it is outside the 'Uniqueness domain'.

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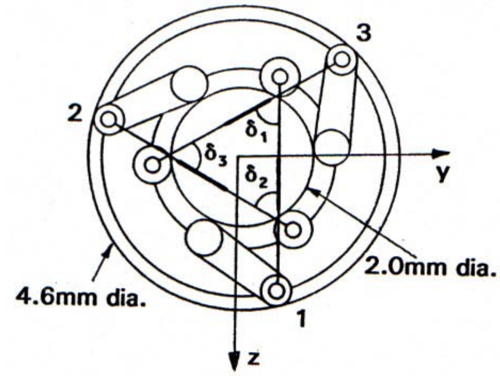
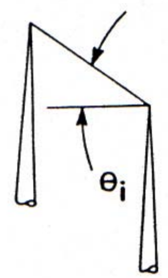
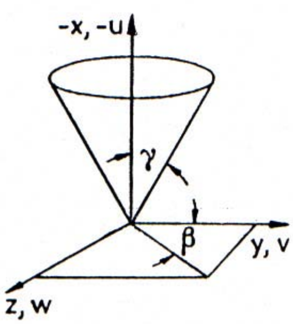


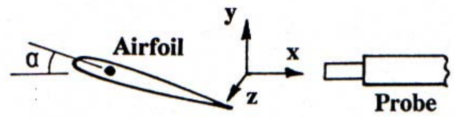
(a) End View



(b) Side view of a sensor



(c) contd.



(c) Coordinate system and flow angles

Fig. 1 Geometry of the 3-sensor probe and the coordinate system used.

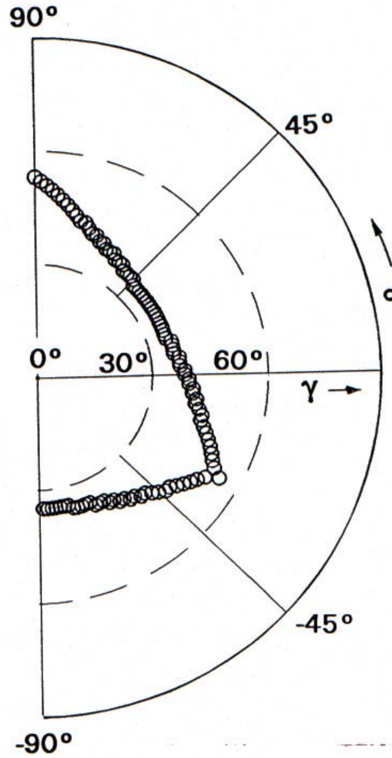


Fig. 2 Uniqueness domain of 3-sensor probe.

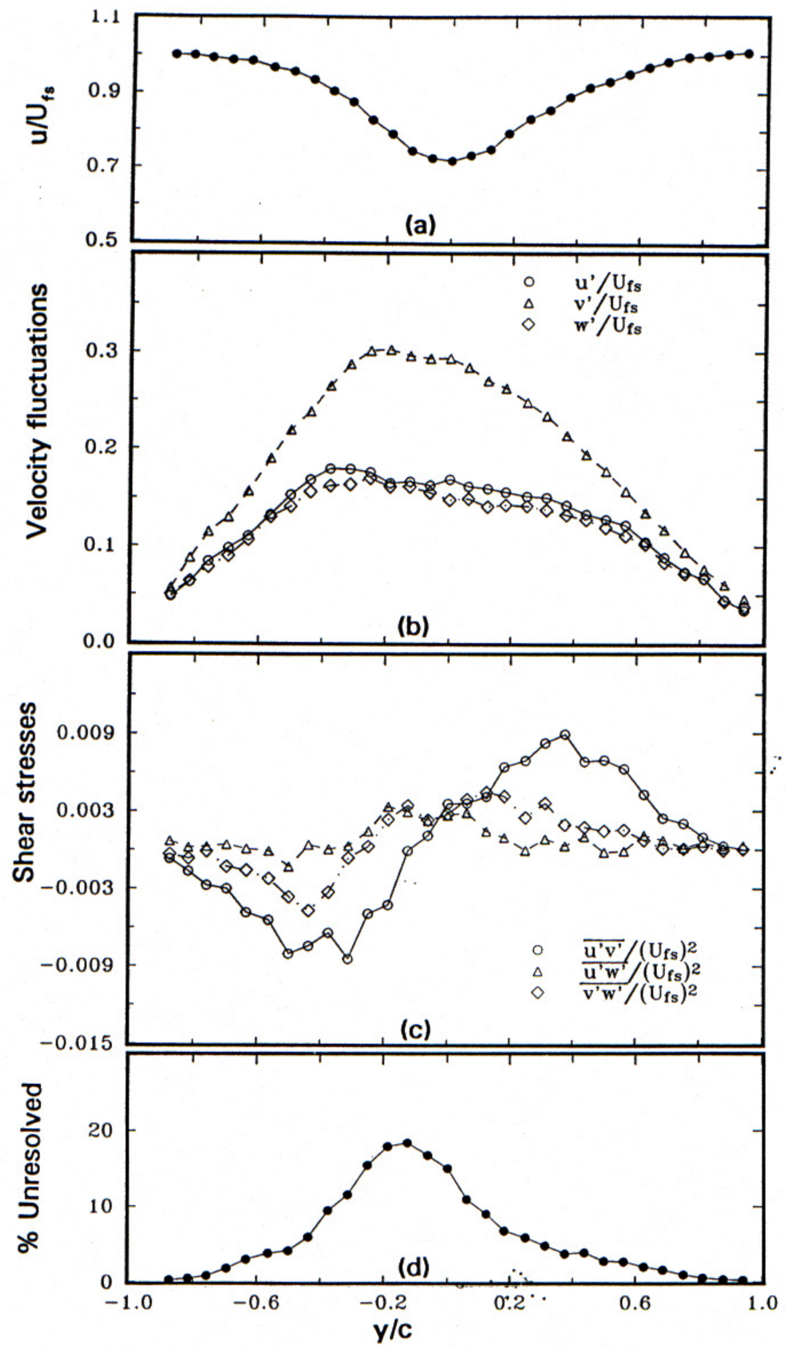


Fig. 3 Measurements in the wake of NACA0012 airfoil at 22.5° angle of attack; x/c=2.5.

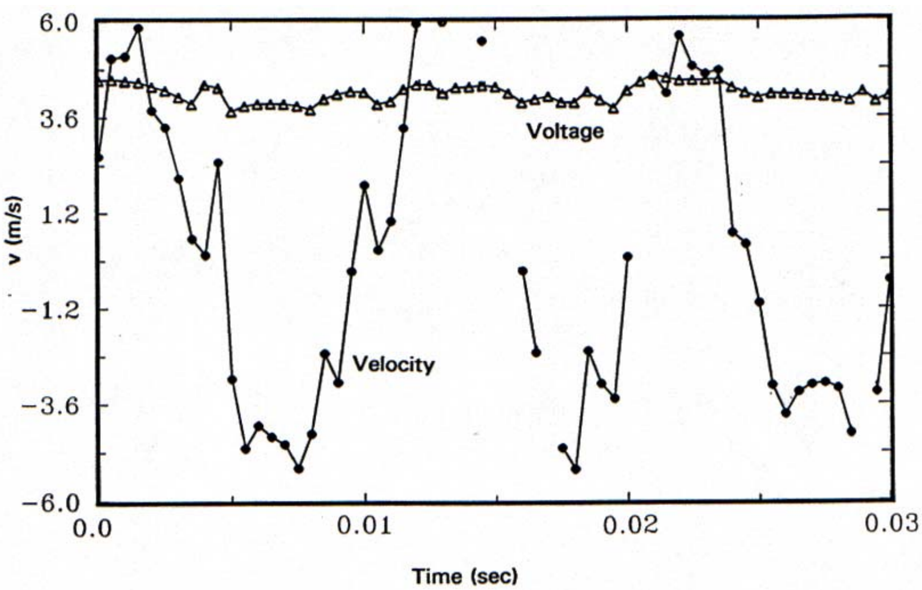


Fig. 4 Time trace of the voltage signal from one of the sensors and V-component of the resolved velocity vector; x/c=2.5, y/c=0.

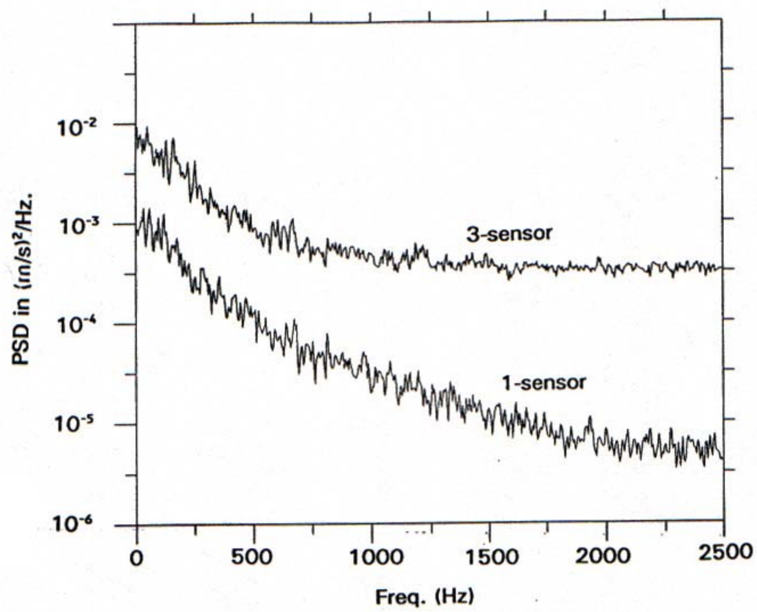


Fig. 5 Velocity spectra obtained using 3-sensor and 1-sensor probes. The former is shifted by 1 major div. NACA0012 airfoil at 2° angle of attack; x/c=4, y/c=.125.